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by

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# ROLE AND SOURCE OF CORPUSCLES OBSERVED IN THE IONOSPHERE AND AURORAS

G. S. Ivanov-Kholodnyi

## SURVEY

Various types of corpuscles have been observed in the upper atmosphere. Their various aspects have been investigated by many methods. Much has been written on this subject recently. This survey discusses only corpuscular fluxes which, first, consist of electrons and second, penetrate the atmosphere to a considerable depth. These corpuscular fluxes appear to play an important part in the formation of ionospheric phenomena and auroras. Some fundamental problems as to their source and origin arise in the study of such corpuscular fluxes. It is also important to elucidate the conditions of their passage through the atmosphere, which are associated with the ionization and glow of the latter. Many of these questions have not yet been answered, and attention should therefore be focused on them.

The explanation of auroral glow was the first problem in the physics of the upper atmosphere. However, it still remains unsolved, although many questions concerning the upper atmosphere which arose much later and even quite recently have already been answered. The auroras have a maximum recurrence and intensity in the 20 to 25$^{\circ}$ zone around the geomagnetic poles, and exhibit a great variety of form; their faint glow is occasionally observed at almost all latitudes [1, 2]. It was observed a long time ago that forceful auroras appear approximately one day after the occurrence of solar flares, and that the activity of the auroras is related to solar activity. Thus, the auroras are manifestations of solar activity. On the other hand, auroras occur simultaneously with geomagnetic storms and occasionally cover

 [redacted]

vast areas of the Earth; they can therefore be regarded as a global geophysical phenomenon. These characteristics of auroras have called for the formulation of a theory which would explain the auroral glow by means of fluxes of charged particles travelling from the Sun to the Earth. The first such theory was put forward by Birkeland and improved by Vegard and Stoermer. This theory seemed to provide an adequate explanation of the auroral bands and their relation to geomagnetic perturbations. The trajectories of the motions of charged particles in a magnetic field were studied in detail. However, upon closer examination, this theory in its initial form could not provide a satisfactory quantitative explanation of such facts as the distribution of particles in the interstellar medium between the Earth and the Sun, the ability of the particles to overcome the magnetic field and atmosphere of the Earth, the characteristics of the action of the particles on the geomagnetic field and the nature of the change in the latter, the excitation of characteristic auroral glow, etc. Chapman, Ferraro and Martin, Bennett and Halbert, Alfven, Petukhov and others have contributed to the improvement and development of theory. We shall not consider these theories here, since a detailed survey and critique of these theories was recently given by Chamberlain [3]. Because of the great difficulties arising in the explanation of auroras and geomagnetic perturbations by the direct action of comparatively slow solar corpuscles, other theories were developed which treated the acceleration of charged particles in the upper atmosphere of the Earth above the auroral zone. At the present time, various kinds of data have made it clear that ordinary auroras are excited by electron fluxes with energies of 10 kev and less [2, 4, 5], and for this reason the theory should explain the appearance of fluxes of such electrons. Somewhat less powerful fluxes of similar soft electrons have been observed in the ionosphere. Today, one of the crucial problems in the theory of the nocturnal ionosphere and auroras is elucidation of the mechanism and origin of the fluxes of soft electrons which produce the ionization and glow of the upper atmosphere, and their relation to solar phenomena and geomagnetic storms.

When the studies with artificial earth satellites and space rockets detected the radiation belts of the Earth, which consisted of fluxes of electrons and protons and whose "horns" projected out into high geomagnetic latitudes, it was natural to associate the origin of auroras with these fluxes.

It is interesting to note that a whole year before the discovery of the radiation belts, Singer [6], working on a theory for the interpretation of the magnetic storms and auroras with the aid of shock waves originating in the sun, proposed a mechanism for the trapping of charged particles in Stoermer's forbidden regions of the magnetic field of the Earth. He showed that the particles with small angles between the velocity and the magnetic line of force may reach deep layers of the atmosphere and produce auroras, the glow of the night sky, and the ionization of the ionosphere.

After the discovery of the radiation belts of the Earth, other sources were proposed for the replenishment of these belts with particles. Most widely accepted was the hypothesis, developed by Singer [7], Vernov et al [8], Kellogg [9], and Hess [10], according to which the formation of the belts was due to the disintegration of the albedo neutrons. This hypothesis was developed in detail by a number of investigators in 1959 - 1960 [11-14] and subsequently by others.

These studies revealed the change in the flux intensity of the particles in space, the energy spectrum and velocity distribution of the track particles; the lifetimes of the latter were calculated, and the most probable ways in which the particles were lost from the radiation belt were determined. It was also shown that the disintegration of the albedo neutrons may be a source of only the inner, more stable radiation belt. In discussing the relationship between the radiation belts of the Earth and the auroras we shall consider the hypotheses concerning the formation of the outer radiation belt. Let us note, however, that Pizzella [15] recently detected substantial variations of radiation intensity in the inner radiation belt following intense chromospheric flares. These variations are so great and the characteristic time of the reestablishment of the normal intensity level is so short that there arise some grave doubts that the neutrons are the only or the main source of the inner radiation belt.

A great stimulus but at the same time the touchstone of the theories concerning the origin of radiation belts and the leakage of particles from the belts was the study of their relationship to the auroras and the Earth's ionosphere. Let us first examine the problem of the relationship with the auroras since it appears to be rather clearly defined.

## EXPERIMENTAL DATA ON THE RELATIONSHIP BETWEEN RADIATION BELTS AND AURORAS

One of the factors which originally suggested a relationship between the radiation belts and the auroras (Van Allen et al [16, 17], Rhodes [18]) was the discovery of the proximity of the latitudes of the auroral zone to those of the emergence of the magnetic lines of force from the outer radiation belt. V. I. Krasovskii et al [19, 20] related the emergence of the radiation belts into high latitudes to the heating and expansion of the atmosphere in these regions. The power of the electron flux measured in the outer belt corresponded as it were to the power of the electron fluxes in the auroras. The first measurements of the radiation intensity fluctuations in the lower parts of the belts [21] showed that they are correlated with the solar magnetic and ionospheric activities including auroras. It seemed natural that in the course of geomagnetic perturbations, when the regular character of the magnetic field is disturbed, the particles are enabled to emerge from the radiation belts. Reaching downward into the denser layers of the Earth's atmosphere, they can cause auroras [11] and a sporadic intensification of ionization in the ionosphere. Therefore on the basis of various considerations, the radiation belts originally appeared to be natural sources of auroras. It was also necessary to take into consideration the fact that the solar activity affected the auroras.

Theories began to be advanced which related the formation of the outer radiation belt to the solar corpuscular fluxes: I. S. Shklovskii et al [11], Rees and Reid [22], S. B. Pikel'ner [23], Gold [24]. Although the approach of these authors to the solution of the fundamental problem of trapping by the magnetic field of particles and plasma clouds from solar corpuscular fluxes was different, nevertheless another fundamental problem remained unsolved in all of the above studies: that of the transfer of energy from the slow ions of the corpuscular flux to the fast electrons of the radiation belts.

Further investigations were conducted both in theoretical research - refinement of the mechanism governing the trapping of particles and their acceleration, explanation of the mechanism governing the escape of the particles from the belts, and their lifetimes - as well as along the lines of accumulation of new experimental data on the spectrum and flux intensities of particles at various heights, on the angular distribution of their velocities, and variation with time and the correlation with various phenomena. We shall examine these studies at some length.

One of the most graphic manifestations of the intimate relationship between the radiation belts and the geomagnetic field are the considerable variations in the intensity of particle fluxes in the belts during geomagnetic storms. The investigations carried out by Rothwell et al [25] with the aid of the satellite Explorer IV and Arnoldy et al [26] with the aid of Explorer VI showed beyond any doubt that during the period of development of geomagnetic storms the radiation intensity in the belts decreases substantially, and after the storm is not only reestablished but increases in comparison with the intensity preceding the magnetic storm. During the storm a change in the profile and size of the outer radiation belt was observed as well as a change in the energy spectrum of the particles, which become harder during the storm. All this indicates the complexity of the mechanisms governing the escape and replenishment of the particles of the belts. In addition to the recognized possibility of replenishment of the outer belts with solar corpuscular fluxes, the idea was suggested in ref. [26] that the change of the particle flux in the belt may be due to the increase in the density of the atmosphere at great altitudes in the course of the geomagnetic storms, when certain processes which accelerate the particles in the atmosphere are intensified. If this were the case, since the increase in the density of the upper atmosphere is due to the solar activity [27-30], this could account for the observed [31] dependence of the radiation intensity in the outer zone on solar activity.

When the position of the radiation belts in the Earth's magnetic field was thoroughly investigated, it was found [25, 26, 32-35], that the magnetic lines of force emerging from the outer radiation belt reached latitudes which do not coincide with the auroral zone, and a particularly pronounced difference in latitudes was noted in the southern hemisphere. Thus, only the outermost portions of the radiation belt are able to yield particles for the excitation of auroras through leakage of the particles out of the outer belt, since it is necessary to assume that the particles are transferred from the central portion of the zone to the outer portion. Moreover, the "Argus" experiment showed that envelopes of trapped particles are very stable with time and that no overflow of particles into magnetic envelopes with a different geomagnetic latitude is observed.

An experimental check was also applied to the major assumption that the intensity and spectrum of the particles in the radiation belts correspond to the intensity and spectrum of the particles in the auroras. In this case it was important to compare the measurements of the corpuscular fluxes made at heights of about 100 kilometers by means of rockets, with measurements of the corpuscular fluxes in the radiation belts, particularly in the lower portions of the radiation belts. We shall consider this problem in more detail, since it is of fundamental importance for the theory which is expected to account for the excitation of the glow in auroras and for the ionization in the ionosphere.

## EXPERIMENTAL DATA ON THE CORPUSCLES IN THE AURORAS AND THE IONOSPHERE

Although many experiments have been carried out with rockets and satellites equipped to measure penetrating radiation, very few data have been obtained thus far on the intensity and energy spectrum of the corpuscular radiation passing through the ionosphere. This is because, after the discovery of the radiation belts of the Earth, all attention was concentrated on the study of the maxima of these belts and on determination of their external boundaries, since these data could be of great importance in evaluating the radiation hazard of cosmic flights (see [36]). In this survey, on the contrary, we are interested in the lowest portion of the radiation zones which extend into the ionosphere and interact with it. As we know, the ionosphere and polar auroras are located considerably below the maximum of the zones, which is located at a height of about 3,000 to 4,000 kilometers about the equator and at high latitudes drops to about 500 kilometers.

The corpuscular radiation in the upper atmosphere at comparatively low altitudes (about 100 kilometers) was first observed by Van Allen and coworkers by means of rockets in 1953. The penetrating radiation was recorded with relatively thick-walled (0.1 - 0.4 g/cm$^2$) Geiger counters at heights $>$ 50 km in the polar region by Meredith, McDonald, Ellis, Van Allen and others [37-39]. In the author's view, only electrons with energies $>$ 1 meV were recorded, whose flux (assuming an isotropic distribution) was about 10 to 20 electrons/cm$^2$ sec. These results were confirmed by the data obtained with a scintillation counter [40, 41]. However, there was no certainty that electrons, rather than protons or $\gamma$ rays, were observed [42]. At the moderate height of about 50 km, the effect due to the corpuscles amounted to a slight addition to the background of cosmic rays, but at a height of 100 km a thin-walled counter recorded a radiation which was already five times more intense than the cosmic rays. Investigations performed between 1953 and 1955 showed that the corpuscular radiation fluctuates strongly with time and has a strongly defined latitude variation with the maximum at the geomagnetic latitude of 65 to 70$^\circ$, i.e., near the maximum of the auroral zone. This was proof that the corpuscles possessed an electric charge.

Subsequent investigations carried out by Van Allen by means of scintillation counters [43-45] showed that the primary corpuscular radiation consists of electrons with energies mainly between 10 and 100 keV (in any event less than 200 keV). In the region of the maximum of the zone of corpuscular radiation, the electron flux was $10^6$ - $10^8$ electrons/cm$^2$ sec (energy flux of 1-0.01 erg/cm$^2$ sec); these electrons are braked at heights of

90 to 110 km and generate braking X-ray radiation with an intensity of $10^3$ - $10^5$ quanta $cm^{-2}$ $sec^{-1}$, which penetrates to a height of about 50 km and sometimes even to 25 km [46].

In the work of Antonova et al [47, 48] it is reported that when fluorescent screens with the ZnS (Ag) phosphorus were used, a number of experiments at heights of 70 to 100 km at middle latitudes in the polar region recorded electron fluxes of 1 to 5 times $10^{-2}$ erg/$cm^2$ sec sterad, whose maximum of the energy spectrum was 10 to 40 keV. The electron flux changed considerably from one day to the next and was sometimes even less than $10^{-2}$ erg/$cm^2$ sec sterad. These results were recently confirmed by Kazachevskaya et al [49], who made measurements at this same height with a different method involving the use of thermoluminescent $CaSO_4$ (Mn).

In ref. [44] it was also shown that the intensity of the corpuscular flux during the maximum of the solar activity in 1957 was three times as high as between 1953 and 1955.

All these experiments, carried out with rockets, show beyond any doubt that at heights of 70 to 100 km there exists a permanent electron flux with an effective energy of 20 to 50 keV. The intensity of the electron flux fluctuates considerably with time, apparently changing by 1 to 2 orders of magnitude. The power of this flux is significant, about $10^{-2}$ erg/$cm^2$ sec sterad, and in the region of geomagnetic latitude of $67^o$ attains a maximum of about 1 to 0.1 erg/$cm^2$ sec sterad.

The heavy dependence of the intensity of the corpuscular radiation being studied on the latitude with a sharp maximum at the geomagnetic latitude of $67^o$, which is located in the vicinity of the auroral zone (similar results were obtained for the southern polar region [45]), as well as the very high intensity of this radiation compared to the energy radiated by the auroras in the visible portion of the spectrum led Van Allen [45] to the conclusion that the corpuscular radiation causes auroras or is in some way associated with them.

## MEASUREMENTS OF ELECTRON FLUXES IN AURORAS BY MEANS OF ROCKETS AND SATELLITES

When a rocket was launched on August 14, 1957 into the luminous formations of auroras, very intense corpuscular fluxes [44] penetrating to a particularly great depth in the atmosphere were recorded [45].

Later several rocket launchings were made to measure the intensity and spectrum of the primary corpuscular radiation. McIlwain [50, 51] reports some results of measurements of ion and electron fluxes in a diffuse aurora in the class of intensity 1 produced along the launching of a rocket on February 21, 1958, and in the active arc of the aurora of February 25, 1958. Corpuscles of about 3 to 250 keV were recorded with a scintillation counter with a CsI crystal combined with electromagnetic spectral analyzers. Electrons began to be recorded at a height of 80 km (the flux being about 0.1 erg/cm$^2$ sec sterad), and their flux was $1.6 \times 10^{10}$ electrons/cm$^2$ sec at the maximum height of 120 km reached by the rocket. Most of the energy was carried by soft electrons with energies $<$ 10 keV. The energy spectrum of electrons in the region of 3 to 30 keV was $2.5 \times 10^9\ e^{-E/5\text{keV}}$ electrons/cm$^2$ sec, and the total energy flux was about 20 ergs/cm$^2$ sec in the diffuse aurora. Also recorded was a flux of 80 - 250 keV protons with a spectrum of the form $j(>E) = 2.5 \times 10^6 \exp\left\{\frac{E}{(30\text{ keV})}\right\}$ protons/cm$^2$ sec sterad and a total flux of about $1.5 \times 10^7$ protons/cm$^2$ sec. In the active auroral arc there was recorded a nearly monoenergetic flux of about 6 keV electrons and a maximum flux of about $5 \times 10^{10}$ electrons/cm$^2$ sec sterad (about 2000 ergs/cm$^2$ sec) [51]. The efficiency of conversion of the energy of electrons into light energy of radiation in the atmosphere was around 0.2%. This important factor makes it possible to determine the intensity of the electron flux in various auroras from a visual evaluation of their intensities.

Meredith and co-workers [52, 53] report on three rocket launchings into the luminous arcs of auroras on January 25 and March 15 and 22, 1958. The rockets were equipped with Geiger counters and proportional, pulsed, and scintillation counters. This made it possible to measure not only the intensity of the corpuscular radiation but also the energy spectrum of the particles constituting it.

When the rocket passed through the luminous auroral formations a flux (up to 5 ergs/cm$^2$ sec sterad) of relatively soft electrons with energies $\geqslant$ 3 keV was recorded. Some data were also obtained on the energy spectrum of the electrons; thus, the intensity of a flux of electrons with energies $\geqslant$ 8 keV was 10 times greater than that of a flux of electrons with energies $\geqslant$ 35 keV. Furthermore, just as in [50, 51], an ion flux of about $10^5$ particles/cm$^2$ sec sterad was recorded whose power was 2 orders of magnitude smaller that of the electron flux. At heights below 130 to 140 km a drop in the intensity of ion and electron fluxes was observed, and the isotropy of the angular velocity distribution of the particles was disrupted. It was noted that the electron flux above 140 km was not constant and in one experiment had three maxima corresponding to the three events of the penetration of the rocket into the rays of the auroras. In contrast to electrons, which were not detected outside the regions of auroral glow, ions were present in the upper layers independently of the aurora. It is important to note that no electrons with the low energy of 30 to 1,000 eV were observed up to a height of 178 km within an accuracy of $10^9$ cm$^{-2}$ sec$^{-1}$ sterad$^{-1}$.

An interesting result was obtained with the satellite Explorer VII

[54], which, upon passing over the auroral arc at a height of 1,000 km (if the trajectory of the satellite is assumed to follow a magnetic line of force), recorded an extremely powerful flux of corpuscular radiation ( $10^4$ ergs/$cm^2$ sec). As in the auroral region, the recorded corpuscular radiation was especially soft (the ratio $j(>30 \text{ keV})/j(> 70 \text{ keV})$ was 27:1 instead of the usual 14:1). The angular velocity distribution of the particles was such that most of them should have been absorbed in the atmosphere after a few hundred oscillations (in a time of several dozen minutes). An intense flux of corpuscular radiation was also detected as the satellite passed over a broad, elongated auroral arc which glowed in the 6300 angstrom line, and the intensity of the corpuscular radiation decreased synchronously with time as the auroral glow faded.

Recently O'Brien et al [55-57] have obtained important new data on the spectrum and intensity of the trapped particles in the lower and central portions of the radiation belts by means of the satellites Explorer XII and Injun I. They found that the estimates of electron fluxes assumed earlier for the outer radiation belts, $10^{11}$ $cm^{-2}$ $sec^{-1}$ ($E>20$ keV) were much too high. The most recent data on the fluxes and spectrum of electrons in the central portion of the outer radiation zone obtained with the aid of Explorer XII are given below:

| | | | | | | |
|---|---|---|---|---|---|---|
| E, keV | >40 | 45—60 | 80—110 | 110—1600 | 1600—5000 | >5000 |
| j, $cm^{-2} \cdot sec^{-1}$ | $\sim 10^8$ | $9 \cdot 10^7$ | $8 \cdot 10^7$ | $<10^8$ | $2 \cdot 10^5$ | $<10^3$ |

According to the measurements made by Injun I, at a height of about 1000 km the particle flux with $E>40$ keV has $j \approx 10^6$ $cm^{-2}$ $sec^{-1}$, and the maximum total energy flux $E>1$ keV was about 10 ergs/$cm^2$ sec sterad according to one detector and about 70 ergs/$cm^2$ sec sterad according to another. In these fluxes there are sometimes observed such small angles between the velocity of the electrons and the magnetic line of force that a large percentage of these electrons should migrate from a height of 1,000 km to about 200 km and, by becoming absorbed, should produce auroras. It is quite possible that the diffuse aurora glowing about continuously in the entire sky and observed during IGY was due precisely to these electron fluxes which had very low pivoting points [5]. The value of j changes considerably with time and depends on the geomagnetic latitude, forming a broad peak at $\varphi_m \approx 50°$ and around the auroral zone. A change was observed in the character of the spectrum of the electrons, which as a rule have a steeper spectrum at high latitudes, i.e., softer corpuscles predominate in the electron flux. In the auroral zone, j changes by an order of magnitude in a few seconds, which corresponds to a satellite displacement of a few dozen km. It should be noted at this point that the first investigations of soft corpuscular radiation performed with the third Soviet artificial satellite by means of a fluorescent detector by Krasovskii et al [58, 19, 20] discovered exactly the same characteristics of the corpuscular radiation.

Of the instruments mentioned so far, the most appropriate for the study of soft corpuscular radiation is a fluorescent screen with a photomultiplier described by Krasovskii, Kushnir and Bordovskii [59]. The third Soviet AES performed measurements by means of a fluorescent screen of ZnS (Ag) of high sensitivity to soft electrons, and valuable results were obtained although there were very few satisfactory measurements (only the orbit of May 15, 1958), because the readings were off scale most of the time [60, 58, 19, 20]. The threshold of sensitivity of the instruments to $\sim$10 keV electrons was the lowest of all the devices used until then. At heights of 470 to 1,880 km the energy flux of the corpuscles usually exceeded the colossal value of $4 \times 10^3$ ergs/cm$^2$ sec sterad. The lowest intensity was recorded above the geomagnetic equator in the inner radiation belt at a height of

1,300 km (in the eastern hemisphere). Whereas the energy of the electrons was $\sim$ 20 keV, their flux was $10^{-14}$ A/cm$^2$ sterad=6 x $10^4$ electrons/cm$^2$ sec sterad [19]. During the night of May 15, the satellite passed over the Pacific Ocean at a height of 1,720 to 1,880 km (southern latitudes of 42 to $54^\circ$). During that time there was observed a change in the intensity and energy of the electrons in the flux as a function of the rotation of the satellites and of the changing geographic latitude, as well as very fast (about 1 sec [60]) time variations in intensity amounting to 1 order of magnitude. In the vicinity of the equator the energy of the electrons was about 40 keV and it dropped to 10 keV in the polar region. In these experiments it was observed that the particles have a predominant direction of motion that is perpendicular to the magnetic lines of force; this indicates that the particles move in spirals about the lines of force. The disk-like velocity distribution of the particles was later confirmed by Van Allen et al [16] and Holly et al [61]. The minimum flux power recorded in these experiments at low altitudes was about 1 erg/cm$^2$ sec. However, this value was also much greater than the power of the particle fluxes recorded by other methods. These experiments are a graphic illustration of the fact that the major part of the energy is carried by soft electrons both in the outer and in the inner radiation belts.

In ref. [60, 58, 19, 20] ideas were advanced concerning the great geophysical importance of these electron fluxes, which are capable of causing a considerable heating of the Earth's upper atmosphere, the observed sharp vertical temperature gradient, and the expansion or swelling of the atmosphere detected by satellites in the polar regions where the intensity of the electron flux is higher. Subsequent investigations confirmed the fact that electrons carry the bulk of the energy in the radiation belts.

According to new data [56], an electron flux with $E > 1$ keV attains about 10 to 70 ergs/cm$^2$ sec sterad, and the angles between the velocity of the electrons and the magnetic line of force are so small that most of the electrons should reach heights of about 200 km and cause auroras. A thorough study of the angular distribution of electrons [57] shows that at different latitudes the intensity of the flux of electrons with $E > 40$ keV, which penetrate deep into the atmosphere, usually amounts to $\sim 10^4$ cm$^{-2}$ sec$^{-1}$ sterad$^{-1}$ [56], i.e., the total flux of the electrons escaping into the dense layers of the atmosphere by day is = $\sim 0.1$ erg/cm$^2$ sec. As will be shown below, a flux of approximately this magnitude or slightly more intense is necessary to maintain the ionization of the nocturnal ionosphere.

## PROBLEM OF THE ACCELERATION OF CORPUSCLES IN THE ATMOSPHERE

The results obtained are of fundamental importance since they again pose the problem of the origin of the corpuscles, auroras, and particles of the radiation belts. The powerful particle fluxes which continually stream into the atmosphere and are observed at comparatively moderate heights, $\sim$ 1,000 km [56], cannot result from the leakage of the trapped particles from the belts. For this reason, references [56, 57] point out that it is necessary to postulate the existence of a certain considerably more powerful mechanism of their acceleration, which operates in the ionosphere. It is possible that the radiation belts are generated by the same mechanism, when accelerated electrons reach the trajectories of magnetic traps. Some ideas on the acceleration of soft particles in the magnetic field of the Earth have been expressed earlier by Krasovskii et al [58, 62] in connection with the data obtained from the third Soviet AES. The same conclusion was reached in our paper written in cooperation with Antonova [77, 78]. Recently, Vernov et al [63], using the data from the second cosmic ship, also discovered important particle fluxes in the atmosphere at the low altitude of 320 km and put forward the hypothesis of a local acceleration of electrons within the confines of the geomagnetic field.

The hypothesis on the acceleration of the particles in the Earth's atmosphere induced by certain processes has been considered by many authors (Alfven, Hoyle, Lebedineskii) in connection with the explanation of auroras and earlier [3]. Essentially, consideration was given to various mechanisms of electron acceleration by hypothetical local electric fields in the ionosphere, whose existence is very conjectural (Fan, [64], Reid [65]). Kellogg [66] assumed that when particles diffuse in the magnetic field of the Earth they are accelerated. Obayashi [67] treated the Fermi acceleration mechanism by hydromagnetic waves. The hypothesis of the acceleration of particles in a static magnetic field as in a kind of geocyclotron was put forward by Helliwell and Bell [68]. Coleman [69] analyzed the influence of an inhomogeneous slowly changing geomagnetic field and the betatron acceleration mechanism. Dessler and Hanson [70] proposed a mechanism of acceleration by the hydromagnetic shock wave which is formed when solar plasma penetrates the Earth's magnetic field. The necessity of postulating the acceleration of particles in the Earth's atmosphere was discussed in detail by Singer [71], Chamberlain [72], and Chamberlain et al [73]. The mechanism of the transresonance acceleration of an electron in the outer portion of the ionosphere in the whistlers was proposed by Parker [74]. Akasofu and Chapman [75, 76] made an attempt to correlate the geomagnetic variations, the radiation belts and the current ring. They thus obtained a unique angular velocity distribution of the trapped particles.

In references [77, 78] L. A. Antonova and the author, proceeding from the hypothesis of the existence of corpuscular electron fluxes in the

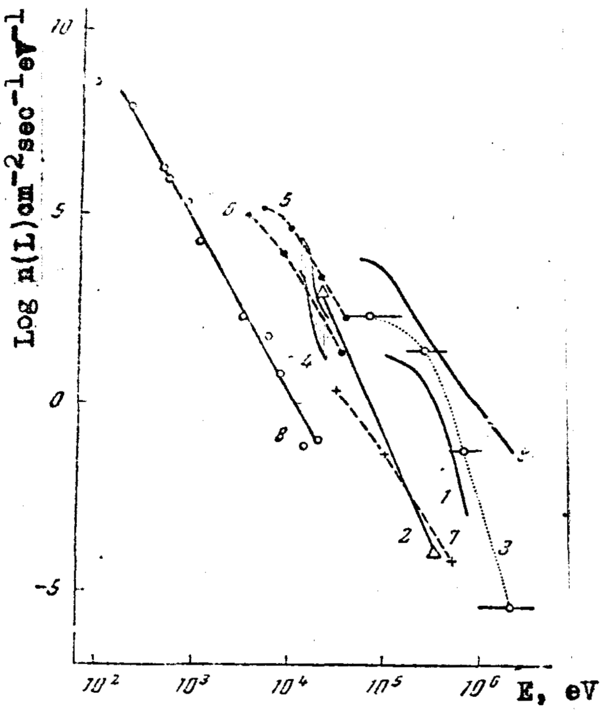


Fig. 1. Energy spectrum of electrons.

1 - data of Cladis et al [98]; 2 - average spectrum calculated by Anderson from X-ray bremsstrahlung [88]; 3 - data of Holly and Johnson [61] (in rel. un.); 4 - data of Krasovskii et al [20]; 5 - data of McIlwain [51]; 6 - data of Meredith et al [52]; 7 - calculated from the data of Kupperian and Friedman [89]; 8 - calculated in ref. [78]; 9 - data of O'Brien et al [55].

ionosphere, calculated the energy spectrum of the electrons maintaining the ionization at night. It was found that the intensity of the electron flux increases with the altitude in the ionosphere. A very small electron energy ($\geqslant$ 100 to 200 eV) in the upper part of the ionosphere and a very steep electron spectrum $N \sim E^{-\gamma}$, where $\gamma = 4.5$ were obtained. A similar spectrum with $\gamma = 5$ was obtained for the corpuscles in the upper atmosphere by Vernov et al [99]. Figure 1 compares the calculated spectrum for quiet ionospheric conditions and various observed spectral data. These calculations were carried out with the assumption of an isotropic velocity distribution of the electrons in space. However, measurements indicate that there is no isotropy. If the true velocity distribution is taken into consideration, it may produce a change in the shape of the calculated energy spectrum of the electrons, as well as a different estimate of the lower limit of the spectrum; however, the magnitude of the total energy flux of the electrons,

$\sim$ 1 erg/cm$^2$ sec, is preserved. According to these studies, electron fluxes are continually present in the ionosphere, and their intensification is caused by ionospheric perturbations and auroras. There is reason to assume that the source of these electrons is situated in the ionosphere itself.

One of the manifestations of corpuscular electron fluxes is the X radiation recorded with the aid of balloons. Let us examine in detail the experimental data on this radiation.

X RADIATION IN THE UPPER ATMOSPHERE

The secondary X radiation generated by the electrons penetrates deep into the atmosphere down to moderate altitudes, so that it can be investigated extensively by simple and inexpensive means, i.e., balloons. During one such very forceful aurora Winckler and Peterson [79] recorded intense X radiation even at a level characterized by a thickness of the atmosphere of 8 g/cm$^2$ (32 km). The intensity of the X radiation with a quantum energy of 50 to 70 keV reached 5 milliroentgens/hr, i.e., about 4 x 10 quanta/cm$^2$ sec (cf. [80]). The mechanism of the bremsstrahlung which is produced when they pass through relatively dense layers of the atmosphere was discussed by Kellogg [81], who showed that for $\sim$50 keV electrons, one quantum of X radiation is formed, on the average for $10^4$ electrons, and that the efficiency of this process is greater for electrons of higher energy. For 300 keV electrons the efficiency is 400 electrons/quantum, according to [82]. Thus, on the basis of the magnitude of the observed flux of X radiation, it may be expected that auroras contain powerful electron fluxes, $\sim 3 \times 10^3$ particles/cm$^2$ sec, this agreeing with the results of direct rocket measurements of these fluxes.

Very intense X radiation from an aurora passing at the zenith was observed on September 23, 1957 by Winckler [83] by means of an ionization chamber attached to a balloon. Winckler estimated the value of the electron flux causing the observed X radiation, and found it to be $8 \times 10^9$ electrons/$cm^2$ sec ($\sim 10^3$ ergs/$cm^2$ sec), assuming that the energy of the electrons was $\sim$100 keV. The same paper reports that on September 13, 1957, a flux 50 times as great was observed. These estimates are somewhat high, due to certain simplifications made in the calculations, and in particular to failure to take into account the spectral energy distribution of the electrons.

In recent years, Winckler, Anderson, Peterson, Arnoldy and others have conducted numerous investigations of X radiation with the use of balloons [82, 84-87]. A correlation of the results of these studies was given by Anderson [88] and Winckler [83].

The most intense fluxes of X radiation were observed during auroras [37, 43, 79, 85, 86] and during violent magnetic storms [84]. Sporadic X radiation is observed for several hours with characteristic wide and rapid fluctuations in intensity.

During the magnetic storm of August 29, 1957, at a height with a residual atmosphere of 11 g/$cm^2$, Anderson [82, 84] recorded a quantum flux of X radiation of 20 quanta/$cm^2$ sec sterad with energy $\geqslant$ 100 keV. Hence, allowing for the absorption outside the atmosphere, the flux should be $\sim$ 75 quanta/$cm^2$ sec sterad. From this value, the electron flux outside the atmosphere (at heights of $\sim$100 km) was estimated [82, 84, 86] to be $6 \times 10^5$ electrons/$cm^2$ sec sterad ($\sim$ 0.2 erg/$cm^2$ sec sterad) or even higher if the assumed electrons were "softer" than 300 keV). It is apparent that even if a relatively great hardness of the electrons is postulated (see above), rather powerful fluxes of corpuscular radiation are obtained in the upper atmosphere, although they are less intense than during forceful auroras. In [82, 84] it is emphasized that, as in the case of auroras, the fluxes change rapidly and are sharply bounded in space.

It is important to note that this radiation was frequently related neither to geomagnetic nor to solar phenomena. Anderson [88] notes that the intensity of X radiation usually decreases after sunset, although this is a rule rather than a law. It is pointed out that in the vicinity of the magnetic pole no X radiation could ever be detected, even during magnetic disturbances.

Let us examine in greater detail the results of observations of X radiation in the absence of auroras and magnetic storms.

During "quiet" periods in the polar region, X radiation was observed during 30% of the total flight time of the balloons [87, 88], but the radiation intensity was 10 to 100 times less than during the auroras. This radiation was recorded with Geiger counters, ionization chambers and scintillation counters, and the results of these experiments served to construct a differential spectrum of photons which is obviously a reflection of the energy spectrum of the electrons which generate this radiation somewhere at heights of $\sim$100 km. The photon radiation flux with an energy $>$ 45 keV amounts to 10 to 100 quanta/cm$^2$ sec.

In order to perform a reliable calculation of the flux of electrons on the basis of the observed X radiation generated by these electrons, it is necessary to know the spectrum of this radiation. Anderson [87, 88] reports on a series of measurements of the spectrum by means of scintillation counters in the polar region during "quiet" periods. The measurements were carried out in three portions of the spectrum: 45--95, 95--170 and 170--340 keV. After the effect of absorption in the atmosphere is taken into account, the three characteristic spectra given in [87, 88] are adequately approximated by the expression $dn(E) = kE^{-\gamma}\,dE$, where $\gamma = 2.3 \div 2.8$ (see figure).

The X radiation spectrum outside the auroral zone in the region of energies between 20 and 1,000 keV at heights of 23 to 114 km was also measured by Kupperian and Friedman in 1954--1957 [89] by means of scintillation counters aboard rockets. It was found that the ascent was associated with a gradual rise in the intensity of the soft quanta and a weakening of the hard ones, so that the total number of quanta remained approximately the same. The data from these thorough measurements of the spectrum at heights of 42--57, 66--75 and 110--114 km, which give concordant results in the 50--300 keV energy region, are shown in the figure. The values of the fluxes on the graph have been multiplied by 10 so that they could be compared with the data of [88]. For energies of 100--300 keV, these results agree with the data of Anderson's measurements [87, 88], but they diverge considerably in the region where $E < 50$ keV. Possibly the data of [88], which were obtained in the polar region during an intensification of X radiation, reflect the specific nature of this phenomenon, during which there may occur an additional increase in the intensity of the softer radiation. It should be noted that even in the region of 100--300 keV the data of [88] are one order of magnitude greater than those of [89].

Thus, the experiments enumerated above show that in the upper atmosphere there is constantly present an appreciable X radiation whose intensity rises considerably in the region of small energies, $\sim$10--20 keV. These fluxes are substantially intensified during auroras and geomagnetic storms. By comparing these data with the results of rocket observations of electron fluxes at heights $>$ 100 km, one can readily conclude that in the upper atmosphere there is permanently present a rather powerful electron flux which manifests itself particularly in the bremsstrahlung of electrons, generated when the latter penetrate into the relatively dense layers of the atmosphere at a height of $\sim$ 100 km. A very important characteristic of this flux is the high rate of dissipation of its energy, due to the absorption of the electrons in the atmosphere, and this flux requires powerful sources to be maintained. It would be desirable also to investigate other phenomena associated with these fluxes.

## INTENSITY OF CORPUSCULAR FLUXES

The first data on the corpuscular radiation in the lower portions of the radiation belts were obtained with Geiger counters designed to measure cosmic rays and therefore insensitive to the comparatively soft radiation which, as was shown later, comprised most of the corpuscular radiation. For this reason, the first estimates yielded very low values of the intensity and high values of the effective particle energy, and at high altitudes the instruments were off scale most of the time, both in the first American and in the first Soviet satellites.

It was mentioned above that the early estimates of the flux intensities of electrons in the radiation belts were high. According to the data of p. 12, a flux of electrons with an energy $E > 40$ keV amounts to $\sim 10$ ergs/cm$^2$ sec. The energy dissipation of this flux is only a minor fraction. Obviously, the power of this flux is not sufficient to cause both the forceful auroras in which electron fluxes having a power of hundreds of ergs/cm$^2$ sec are observed and weaker auroras, since the energy of electron fluxes of 1--10 ergs/cm$^2$ sec is dissipated in these auroras. Thus, according to the observations of O'Brien et al [56, 57], at heights of $\sim$1,000 km in the auroral zone, the fluxes of electrons with $E > 1$ keV reach 10--100 ergs/cm$^2$

sec, and a substantial percentage of the electrons escapes into the atmosphere, producing ionization and excitation of particles of the atmosphere at altitudes of 100 to 200 km. However, these ordinary fluxes are not able to cause ordinary auroras, since for a factor of $\sim$0.2% for the conversion of the energy of the electron flux into radiation (see p. 10) they will produce a glow of only 0.02--0.002 erg/cm$^2$ sec. However, as already indicated, these fluxes can create a diffuse aurora which can be observed against the background of the nightglow.

On the other hand, investigations of elementary processes in the ionosphere [77, 78] have independently led to the necessity of assuming that electron fluxes of 1--10 ergs/cm$^2$ sec exist in the upper atmosphere. According to recent data on the ionosphere [90, 91], the electron fluxes carry 0.1--1 erg/cm$^2$ sec.

Summing up the results of our discussion of the various experimental data on electron fluxes in the ionosphere and auroras at altitudes of 100--1,000 km, we shall emphasize certain particular characteristics of these fluxes.

## ARE TRAPPED PARTICLES THE SOURCE OF AURORAS?

Experiments have shown that the magnetic lines of force project from the outer radiation belt into latitudes located below the auroral zone, while the intensity maximum of the corpuscular fluxes at heights of $\sim$100 km coincides with the auroral zone. Investigations with rockets and satellites have established that during quiet periods in the region of the ionosphere there are observed corpuscular fluxes comparable in intensity to the electron fluxes in the radiation belts. To say nothing of the more powerful electron fluxes which cause auroras, it is possible to state that the energy possessed by the radiation belts is not sufficient to produce even these ordinary electron fluxes in the ionosphere, since the electron fluxes in the radiation belts are comparatively stable, or at least, change slowly, have long lifetimes, and dissipate little energy. In addition, the available data indicate that the energy spectrum of electrons is softer and steeper than in the radiation belts, so that these electrons are absorbed at altitudes of 200--300 km (ionosphere) and $\sim$100 km (auroras), whereas the particles from the radiation belts which are able to penetrate the D layer should produce ionization in the latter and (in consequence) absorption of radio waves. It should be noted that the particle fluxes which cause auroras carry such high energy that the dipolar character of the Earth's magnetic field has no effect upon them. In this connection, the fact observed during IGY that the geomagnetic longitudes and periods of auroral glow coincide in both hemispheres, requires a special explanation. Lately, however, this coincidence itself has become a subject of controversy.

Other arguments could have been advanced against the mechanism of the formation of electron fluxes which excite auroras from the particles of the radiation belts. It is apposite only to add that the mechanisms discussed in the literature which govern the escape of particles from the radiation belts cannot assure formation of the necessary powerful electron fluxes. On the other hand, it is obvious that if the radiation belts are formed from cosmic rays which carry an energy of only $10^{-3}$--$10^{-4}$ ergs/cm$^2$ sec, they are not able to maintain electron fluxes which give up $\sim$1 erg/cm$^2$ sec to the ionosphere. There is no doubt that electron acceleration mechanisms operate in the uppermost parts of the atmosphere which possibly draw energy from the energy of the geomagnetic field. Moreover, it is not impossible that the radiation belts of the Earth, which manifest a relationship with the electron fluxes in the atmosphere, are also formed to a certain extent as a result of the same mechanisms. However, this problem requires further investigations.

## MECHANISMS OF THE DUMPING OF PARTICLES FROM RADIATION BELTS

Perhaps one of the most important problems which should be answered by the theory explaining the auroras by the action of particles from the radiation belts is the problem of how these particles escape into the atmosphere. As was noted above, favorable conditions for the escape of particles are apparently created during geomagnetic perturbations. Other mechanisms for the escape of particles have also been proposed. Rhodes [18], Singer [7], Inoue et al [92] determined the rate of the escape caused by collisions of the particles of the belts with the particles of the atmosphere. A particle from the radiation belt is most likely to collide in the vicinity of the pivotal points, where almost every collision leads to an increase in the angle between the velocity vector and the magnetic line of force, and hence, accelerates the loss of the particle by absorption in the atmosphere. However, this mechanism is found to be quite slow. V. D. Pletnev [93, 94] considered the escape of particles as being due to short-period variations of the geomagnetic field. Regions of low flux intensity of the trapped particles are then formed at certain distances from the Earth; these distances correspond to the observational data. Matsushita [95] analyzed the mechanism of electron dumping under the influence electrostatic fields forming in the upper atmosphere in the course of magnetic storms. The increase of ionization in the F region, the appearance of $E_s$, the increase of $fE_s$ and the increase in the absorption of cosmic radio-frequency radiation in the D region of the ionosphere was attributed by Matsushita to the penetration of electrons from the radiation zones into the atmosphere [96]. Kern and Vestine [97] considered the escape of particles from the belts to be due to the formation of instability in the electron belts as a result of a certain drop of the pivotal points of the trapped particles, but the cause of this drop remains unclear. We have seen that the mechanisms considered cannot explain the formation of powerful, local, repidly changing fluxes of soft electrons.

The results of investigations of radiation belts and auroral particles examined in this survey show that the radiation belts obviously cannot be the source of auroras. We are again faced with the problem of the source of auroras. It is possible that the fluxes of soft electrons, which lose their energy rapidly and excite auroras and the ionosphere, form in the upper atmosphere itself at comparatively low altitudes. It may be [77, 78] that the acceleration of electrons is due to geomagnetic variations at the expense of the energy of the Earth's magnetic field. However, it is obvious that at the present time there is as yet no concrete mechanism to account for the acceleration of these electrons, and the data on the intensity of soft electrons and on the soft edge of the spectrum require additional experimental refinements.


## ABSTRACT

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A review of studies of electron fluxes, penetrating sufficiently deep to the Earth's atmosphere is given. The paper describes experimental data on the intensity and energy spectrum of particles propagating through the ionosphere and the aurorae. Powerful electron fluxes observed in the atmosphere at the heights of 100--1,000 km carried the inflow of energy of 0.1--1 erg/cm$^2$ sec to the ionosphere, which necessary to maintain the night ionization and atmosphere warming. A number of indirect data shows that the source of these electrons is in the ionosphere and not in the radiation belts. The latter themselves are evidently the result of the effect of these acceleration mechanisms, in which some part of particles may get to the trapping trajectory. The concrete mechanism of particles acceleration and their source is not cleared up yet.

Author


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